DEVELOPMENT OF A ROBUST COMPACTION DEVICE FOR LABORATORY SOIL COMPACTION TEST

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ABSTRACT

The commonly used laboratory soil compaction test device is the Proctor. This device provides soil compaction test results for the sizes and weights of 1990s-era compaction equipment which are smaller than the current equipment that induce larger compactive energy. Hence, Department of Transportation in the State of Wisconsin (WisDOT) officials recommended increasing the slice thickness of 20 mm to a maximum allowable slice thickness to reduce construction time and total cost. This recommendation cannot be handled by the Proctor device which employs customized mould. There is therefore a need to design and fabricate a robust device capable of test-compacting variable soil slice thicknesses at varying compactive energies. International Standards (ISO) method of general machinery principle of design was adopted to design and fabricate the components. This includes a 200 mm diameter compactor, to compact the soil samples; a mould of 201 mm diameter, 700 mm high, which holds the soil slices during compaction; a steel rod of length 1190 mm, which holds and directs the compactor during compaction and a removable plate of diameter 200 mm, situated below the compactor, distributes the compactive efforts evenly on the soil specimen. The device was tested by compacting sandy loam soil whose index properties were pre-determined. Compaction results showed that compaction, ΔZ increased with increasing cumulative compactive effort, Ec; the degree of compaction, ΔZ/Z decreased with increasing Ec because, the total loading, Z increased faster than ΔZ; ΔZ/Z decreased with increasing antecedent soil bulk density and with increasing degree of soil water saturation, Se and ΣΔZ/Z decreased with increasing soil slice thickness, z. The results agree with the notional variations of compaction. It is recommended that the design of the device's extruding component be improved because it was difficult to remove the compacted soil samples from the mould after compaction.

Key Words: Robust compaction device, Soil compaction, Laboratory compaction, Proctor compaction device.

1 INTRODUCTION

During the past decades, with the development of building construction and geotechnical engineering, soil improvement by densification has shown much growth in the world, and poor or unstable soils are encountered in many projects. If the encountered soils are compressible or have inadequate strength, compaction is particularly useful. Compaction is capable of achieving significant densification of loose soil. The effect of compaction on soil is the reduction of the volume of voids, thereby leading to an increase in density [1]. The presently available laboratory compaction device is the one designed by Proctor [2]. Two types of compaction tests are routinely performed by the Proctor: (1) the 'Original (Standard)

Proctor' and (2) the 'Modified Proctor' tests. The Original (Standard) Proctor test uses a 101.6 mm mould that holds 0.0009 m^3 of soil and compacts three separate slices of soil using 25 blows by a 2.495 kg hammer falling from a height of 305 mm, for a compactive effort of 60,390 Nm. The Modified Proctor test uses the same mould but a different hammer mass of 4.536 kg falling through a height of 475 mm, with 25 or 56 blows on each of the five slices, for a compactive effort of 273,280 Nm [3]. Both tests allow the use of a larger mould with a diameter of 152.4 mm and holding 0.00213 m^3 of soil sample if the soil or aggregate contains too large a proportion of gravel-sized particles [4]. Summarily, the Proctor compaction device has the following limitations: It is manually operated (ii) a drop of the hammer does not cover the whole surface of the soil specimen (iii) it accommodates only a specified soil thickness of 117 mm and (iv) a maximum of 3 or 5 slices can cumulatively be compacted, and this may not be robust enough to investigate the degree of compaction of soils, especially in embankments such as landfills, dams, roads, levees, etc., which usually involves several numbers of layers to be compacted. Appropriate selection of a cumulative number of slices and the slice thicknesses in embankment construction has important engineering and economic implications in the design, construction, and performance of roads, levees, and dams. Currently, the standard specification from the Department of Transportation in the State of Wisconsin (WisDOT) for road construction recommends a slice thickness of 20 cm Standard Specifications for Highway and Structure Construction [5]. However, this recommendation was based on the size and weight of 1990s-era compaction equipment that was smaller than the current compactors, which induces larger compactive energies [5]. Contractors and WisDOT officials are willing to consider increasing the maximum allowable slice thicknesses to reduce construction time and total cost; however, care should be taken so that the engineering properties of the embankments are not compromised. The concern is that a large increment in slice thicknesses may also produce mechanically unstable embankments due to the reduction of compaction effectiveness, thus leaving regions with low density and poor engineering properties. Therefore, the increase in maximum slice thicknesses has to be technically justified to guarantee the mechanical performance of soil embankments [5]. Therefore, to gain better knowledge of soil compaction using several soil slices of different thicknesses that can generate several soil compaction variables, a robust laboratory compactor was fabricated. The compaction device fabricated has the same mechanical working principle as the Proctor device. The little difference from the Proctor was due to the improvement done on the device, which is (i) mechanically operated to save time, energy, and cost. (ii) accommodates 7 slices of 100 mm thick or even more slices when the thickness reduces and (iii) uses 5 different thicknesses of 20, 40, 60, 80, and 100 mm to yield the major variables affecting soil degree of compaction for appropriate application on field compaction.

2 METHODOLOGY

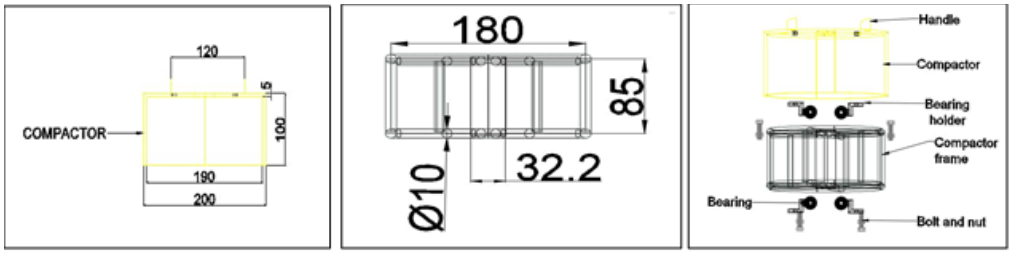
2.1 The Device Fabrication

The compaction device comprises (i) compaction components and (ii) support components. The compaction components consist of four parts, namely, the compactor, mould, steel rod with base plate, and removable plate, while the support components are the compactor riser, support beams, iron ropes, guard pulleys, and support bars. International Standards (ISO) safety of machinery general principles for design were adopted in designing the device.

2.1.1 The Compactor

The compactor is the part of the compaction components that is directly involved in the compaction process; hence, it is the first component that was designed because its weight and diameter were the main concerns. It is cylindrical with the inside containing eight bearings: a set of four on top, set at 90° to one another, and another corresponding set below, held by bearing holders fastened by bolts and nuts inside a casing known as a compactor frame. The compactor frame is 180 mm in diameter and 85 mm thick. Each of the bearings has a diameter of 10 mm and slides up and down along the steel rod during compaction. The bearings help to reduce friction that may occur between the steel rod and the compactor during compaction. Two handles, directly opposite each other, were situated on the top, flat compactor surface for

hooking the iron ropes that lift the compactor during compaction. The compactor was constructed of metal weighing 10 kg and a diameter of 200 mm. A 31 mm hole was provided at the centre of the compactor for the steel rod to pass through. Figure 1 shows the sectional view of the compactor, the frame, and the exploded view of the compactor.

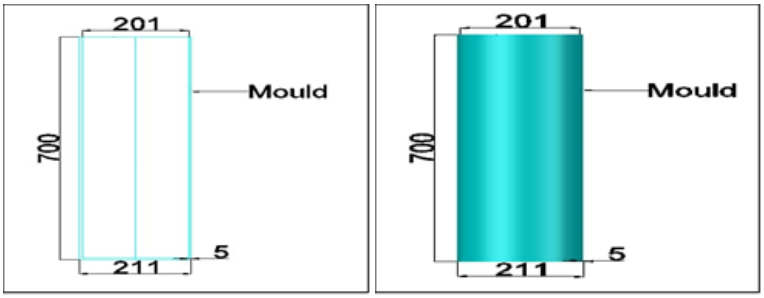


(a) Sectional View (b) Compactor frame (c) Exploded View

Figure 1: The Compactor

2.1.2 The Mould

The International Standards (ISO) Safety of Machinery general principles for design were adopted to design the mould. The mould was constructed of 5 mm thick cylindrical metal according to the shape of the compactor. Its external and internal diameters are 211 and 201 mm respectively, and it is 700 mm high to accommodate several soil slices and slice thicknesses. The mould is strong enough to withstand the pressure of the compacting force. The setup is seen in Figure 2.

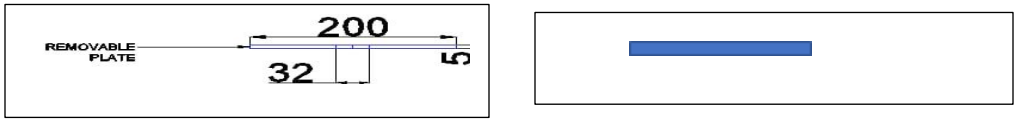


(a) Sectional View (b) Isometric View

Figure 2. Mould

2.1.3 The Removable Plate

The removable plate is a 2 mm thick metal of the same cylindrical shape and diameter as the compactor. It can be removed from the assembly to permit the extruding of the soil samples out of the mould after compaction and allow the re-introduction of new samples into the mould. At its centre, there is a circular hole of 32 mm in diameter for the rod to pass through. This plate is placed on the soil surface to distribute the compaction force evenly to the soil surface. Figure 3 shows the sectional and isometric views of this component.

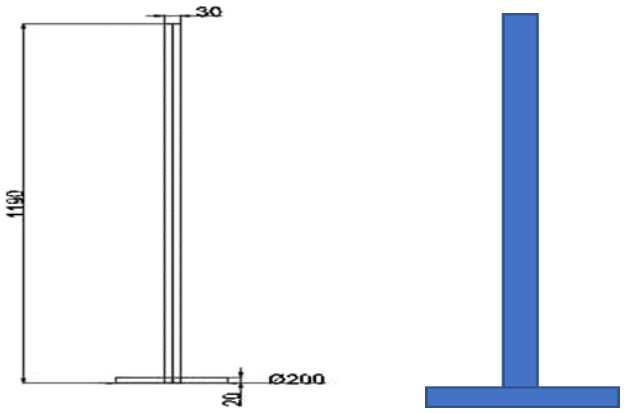


(a) Sectional View (b) Isometric View

Figure 3. Removable Plate

2.1.4 The Steel Rod

The steel rod is 1190 mm long and 30 mm in diameter. It is situated at the centre of the mould and fixed to a 20 mm thick and 200 mm diameter metal plate at its base. The compactor and the removal plate slide along its vertical axis during compaction. The steel rod guides the compactor's height of drop and wobbling during the compaction process. Figure 4 shows the sectional and isometric views of the rod.

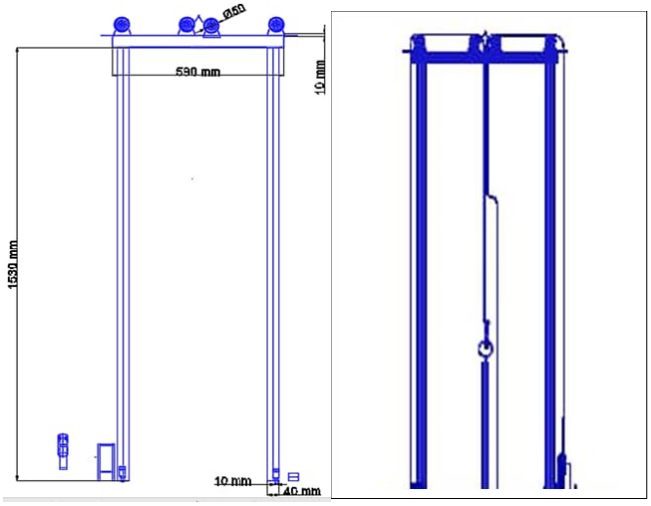


(a) Sectional View (b) Isometric View

Figure 4. The Steel Rod

2.1.5 The Compactor Riser and Support Beams

The risers are two vertical metal rods made of iron 40 mm thick at 590 mm apart and 1530 mm high to provide enough space for lifting the compactor to the designated height during compaction as well as extruding the compacted soil samples after compaction test. The two risers were joined by horizontal beams. Figure 5 shows the risers.



(a) Sectional View (b) Isometric View

Figure 5. Compactor Risers

2.1.6 The Support Beams

Two support beams 1 and 2 of 10mm thick metal were used to provide sufficient strength to bear the compactor weight during compaction and the weight of compacted soil samples during removal from the mould after compaction test. Beams 1 and 2 were fixed to the risers at the bottom and top respectively. The geometry of the beams can be seen in Fig. 5.

2.1.7 Iron Ropes and Guard Pulleys

Two iron ropes, each 30 mm thick and 3,060 mm long, have each end fixed to the compactor and extruder pulleys, and their other ends fixed to the compactor and the extruder handles, respectively [Figure 5 (b)]. The functions of the iron ropes are for lifting and lowering the compactor during the compaction process as well as for expelling the compacted soil samples after the test. Four guard pulleys, 30 mm in

diameter, were welded to the support beam 2 at the top (Figure 5). Two pulleys carry the compactor iron ropes while the other two carry the extruder iron ropes. The pulleys provide ease during compaction and expelling of specimens after compaction.

2.1.8 The Support Bars

Three support bars, each having a width of 38.64 mm, were firmly welded to the mould in slanted positions (Figure 6). Each support bar has vertical and slant heights of 703.8 mm and 718.75 mm, respectively, at equal distances. A square horseshoe clamp of 129.7 mm was welded at their base to prevent any tilts in the support and sinks that may occur and damage the mould while compacting and altering the result. They are made up of metal.

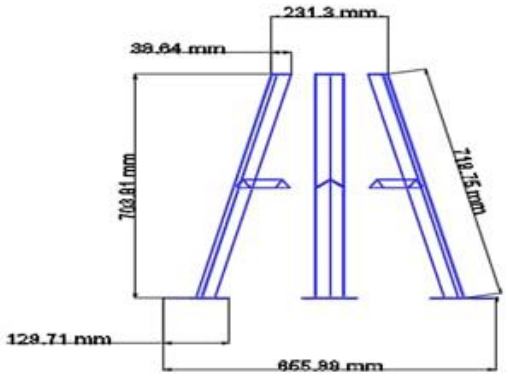
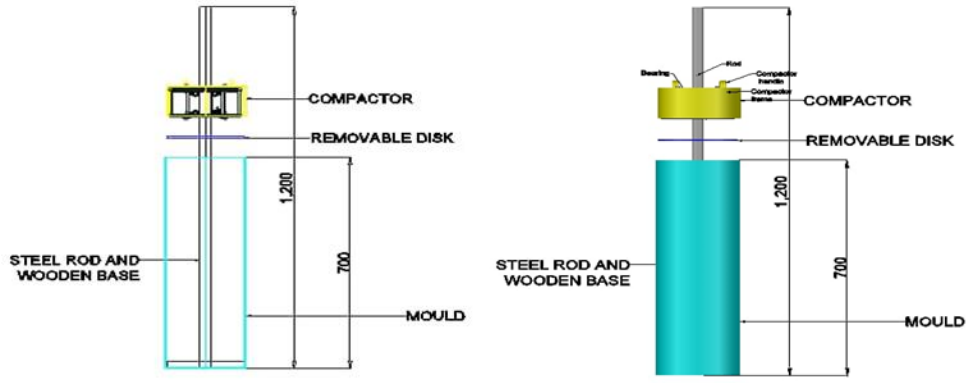


Figure 6. The Support Bars

2.2 Assembling the Compaction Device

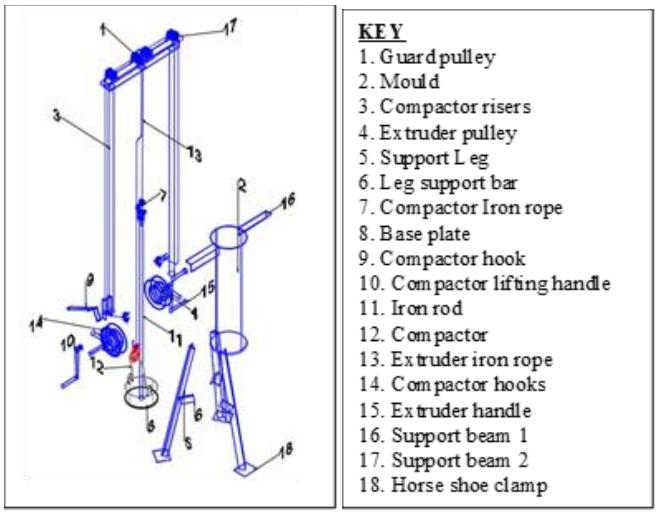
Figure 7a shows the sectional view, while 7b shows the isometric view of the assembled compaction components. The following ways were followed in the assembling of the device. First, the mould was placed on a flat surface; next, the steel rod with its base plate was placed inside and at the centre of the mould; then the removable plate and the compactor mounted the steel rod through their centre holes and released it down slowly to the base plate of the steel rod inside the mould to give the complete assembly of the compaction components.



(a) Sectional View (b) Isometric View

Figure 7. Assembled Compaction Components

Support components were fixed one after the other to the compaction components to reduce the drudgery of compaction. Figure 8 is the complete assembly of the device.



(a) Exploded View (b) Isometric View

Figure 8. Assembly of the Compaction Device

2.3 Device Operation

The device was mechanically operated by lifting the compactor using the lifting device and releasing it suddenly by pressing the compactor hook. The compactor falls on the soil sample surface that was inside the mould. It was then lifted again, and the compaction achieved was measured using a ruler dipped inside the mould. At the end of each compaction cycle, the steel rod was pulled out by rotating the extruder handle, and the soil was expelled. Both the compaction and the extruding processes were repeated for every cycle of the compaction. The device was tested by compacting cumulatively 7 soil slices of 5 different thicknesses ranging from 20 mm to 100 mm using different compactive efforts from 147.15 Nm to 1030.05 Nm.

3 RESULTS AND DISCUSSION

3.1 The Device and Compaction Products

Figure 9 shows the fabricated compaction device, while Figure 10 shows five uncompacted slices and five compacted slices (the compaction products) by the device. The slice thicknesses compacted ranged from 20 to 100 mm using a compactive effort of 1030.05 Nm each.

(a) AutoCAD design of the Device (b) Photograph of the Device

Figure 9. Front Views of the Compaction Device

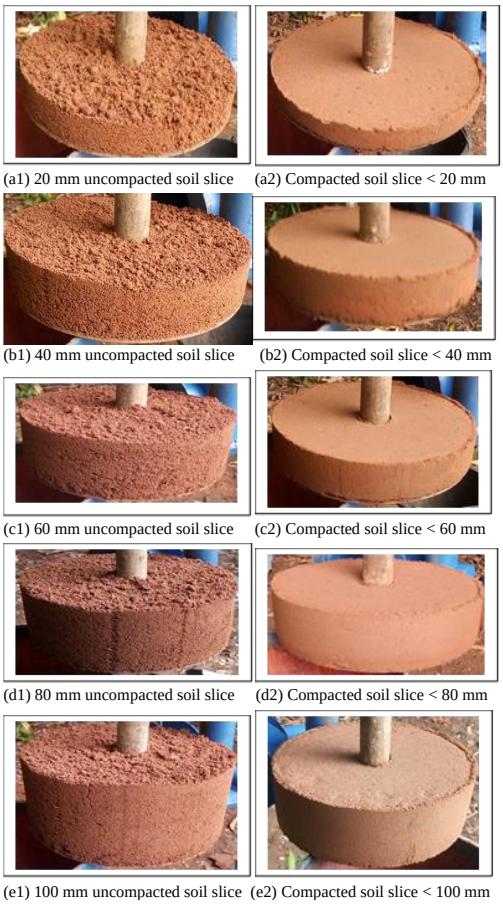


Figure 10 (a – e). Compacted and Uncompacted soil slices

Table 1 shows the specifications of the fabricated device. From the Table, the energy deliverable per drop by the compactor of weight 294.3 N and from a height of 0.5m was 147.15 Nm while the cross-sectional area was 0.0314 m^2.

Table 1. Compactor Operational Variables and Specifications

S/N	Variables	Symbols/Notations	Values	Units
1	Compactive energy (W x h)	E	294.3 x 0.5 = 147.5	Nm
a	Weight	W = mg = 30 x 9.81	294.3	N
b	Height of drop	H	0.5	m
2	Cross-sectional area	A	0.0314	m^2
3	Time of contact	T	Instantaneous	s
4	Slice thickness	Z	0.02 to 0.1	m
5	Acceleration due to gravity	G	9.81	m/s^2

3.2 Results of the Soil Index Properties

Table 2 shows the results of the soil index properties, and Figure 11 shows the grading curve. From particle size analysis of the soil tested, clay, silt, and sand were found to be 18.4%, 27.8%, and 53.7%, respectively. The table also shows that the coarse to fine fraction (C/F) was 1.16 and the uniformity coefficient, Uc, was 6.43. The bulk density was 1511.29 kg/m³. From the grading curve, φ30 = 0.4. The coefficient of curvature, Cc = (φ30)2/(φ60φ10) = 1.27. The grading curve represents the distribution of particles of different sizes in the soil mass [6]. It gives an idea regarding the gradation of the soil, i.e., it identifies whether the soil is well-graded, poorly graded, uniformly graded, or gap-graded. According to [7], well-graded soil is soil with a uniformity coefficient (Uc) greater than 6 and a coefficient of curvature

(Cc) greater than 1 but less than 3. From the result of this analysis, the soil samples were well-graded sandy loam, which means that there is a widespread soil particle distribution of sand, silt, and clay in the soil sample, which is expected to yield compaction well.

Table 2. Soil Index Properties/Variables

S/N	Variables	Notations	Values	Units
1	Soil moisture content	m_c	10	%
2	Bulk Density	ρ_b	1511.29	kgm^{-3}
3	Specific Gravity	Gs	2592.0	kgm^{-3}
4	Mean particle size	φ_{50}	0.6	m
5	Uniformity coefficient	$U_c = \varphi_{60}/\varphi_{10}$	6.43	-
		φ_{10}	0.14	m
		φ_{60}	0.9	m
6	Coarse-to-fine ratio	C/F	1.16	-
	Fine fraction (Silt + Clay)	F	46.2	%
		Silt	27.8	%
		Clay	18.4	%
	Coarse fraction (Sand)	C	53.7	%
7	Coefficient of curvature	$C_c = (\varphi_{30})^2/(\varphi_{60}\varphi_{10})$	1.27	-
		φ_{30}	0.4	m
8	Particle unit weight	γ_s	2592.53	Nm^{-3}
9	Consistency	LL	-	%
		PL	-	%
		PI = LL-PL	-	-
10	Porosity	n	41.69	%
11	Texture	-	Sandy loam	-
12	Unit weight before compaction	γ_{bc}	14825.8	Nm^{-3}

A very important soil property, the specific gravity, was also measured and found to be 2592. The specific gravity gives an idea about the suitability of the soil as a construction material because higher values of specific gravity give more strength to roads and foundations [8]. The soil tested has a high specific gravity, enough to give the needed strength in construction works. It is also used in the calculation of void ratio, porosity, degree of saturation, and other soil parameters [9]. Based on the study [10], the research found that an increase in specific gravity can increase shear strength parameters (cohesion and angle of shearing resistance).

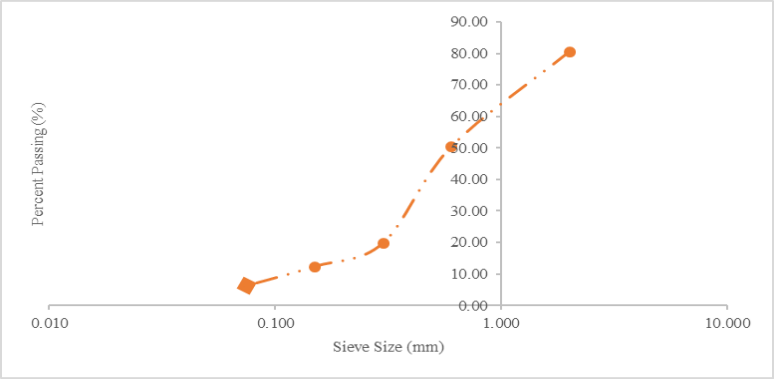


Figure 11. Grading curve

3.3 Notional Variations of Compaction

The data in Table 3 confirmed the following notional variations: (i) compaction, ΔZ, increased with increasing cumulative compactive effort, Ec. [11]; however, the degree of compaction, ΔZ/Zι, actually decreased with increasing Ec because Zι increased faster than ΔZ in this case (ii) the degree of compaction, ΔZ/Zι, decreased with increasing antecedent soil bulk density and with increasing degree of soil water saturation, Se = (γbc γs/(γw(γs- γbc)))m_c [12, 13]. The reason for the later observation appears to be the fact that Se is not independent of γbc as shown above, and as denser soil resists compaction more than

looser soils, $\Delta Z/Z_t$ has to decrease with increasing Se (iii) the degree of compaction, $\Sigma\Delta Z/Z$, decreased with increasing soil slice thickness, z, [14, 13, 15].

Table 3.Test Data Record Matrix for 5 Levels of Soil Slice Thickness (LST) for the 1st Level of Compactive Effort (eL), 147.15 Nm Per loading at 10% moisture content

		e_L		(1) 147.15 Nm/Loading							
1	2	3	4	5	6	7	8	9	10	11	12
LST	z	Z	LEL	E_c	Z_l	ΔZ	E_c	m	γ_{bc}	S_e	$10^2x\Delta Z/Z_l$
1	20	140	1	147.15	0.02000	0.0030	0.0030	0.95	14825.80	0.24	15.00
			2	294.30	0.03700	0.0030	0.0060	1.90	16027.90	0.27	8.1081
			3	441.45	0.05400	0.0035	0.0095	2.85	16473.11	0.28	6.4815
			4	588.60	0.07050	0.0035	0.0130	3.80	16823.61	0.30	4.9645
			5	735.75	0.08700	0.0040	0.0170	4.75	17041.15	0.30	4.5977
			6	882.90	0.10300	0.0040	0.0210	5.70	17272.78	0.31	3.8835
			7	1030.05	0.11900	0.0040	0.0250	6.65	17442.12	0.32	3.3613
2	40	280	1	147.15	0.0400	0.0050	0.0050	1.90	14825.80	0.24	12.5000
			2	294.30	0.0750	0.0060	0.0110	3.80	15814.19	0.26	8.0000
			3	441.45	0.1090	0.0060	0.0170	5.70	16321.99	0.28	5.5046
			4	588.60	0.1430	0.0080	0.0250	7.60	16588.31	0.29	5.5944
			5	735.75	0.1750	0.0080	0.0330	9.50	16943.78	0.30	4.5714
			6	882.90	0.2070	0.0090	0.0420	11.40	17189.34	0.31	4.3478
			7	1030.05	0.2380	0.0100	0.0520	13.30	17442.12	0.32	4.2017
3	60	420	1	147.15	0.0600	0.0070	0.0070	2.85	14825.80	0.24	11.6667
			2	294.30	0.1130	0.0070	0.0140	5.70	15744.22	0.26	6.1947
			3	441.45	0.1660	0.0090	0.0230	8.55	16076.17	0.27	5.4217
			4	588.60	0.2170	0.0090	0.0320	11.40	16397.20	0.28	4.1475
			5	735.75	0.2680	0.0100	0.0420	14.25	16596.05	0.29	3.7313
			6	882.90	0.3180	0.0120	0.0540	17.10	16783.93	0.29	3.7736
			7	1030.05	0.3660	0.0120	0.0660	19.95	17013.22	0.30	3.2787
4	80	560	1	147.15	0.0800	0.0075	0.0075	3.80	14825.80	0.24	9.3750
			2	294.30	0.1525	0.0085	0.0160	7.60	15554.94	0.26	5.5738
			3	441.45	0.2240	0.0100	0.0260	11.40	15884.79	0.27	4.4643
			4	588.60	0.2940	0.0110	0.0370	15.20	16136.93	0.27	3.7415
			5	735.75	0.3630	0.0120	0.0490	19.00	16336.97	0.28	3.3058
			6	882.90	0.4310	0.0130	0.0620	22.80	16511.34	0.29	3.0162
			7	1030.05	0.4980	0.0140	0.0760	26.60	16671.59	0.29	2.8112
5	100	700	1	147.15	0.1000	0.0100	0.0100	4.75	14825.80	0.24	10.0000
			2	294.30	0.1900	0.0100	0.0200	9.50	15606.11	0.26	5.2632
			3	441.45	0.2800	0.0110	0.0310	14.25	15884.79	0.27	3.9286
			4	588.60	0.3690	0.0120	0.0430	19.00	16071.33	0.27	3.2520
			5	735.75	0.4570	0.0140	0.0570	23.75	16220.79	0.28	3.0635
			6	882.90	0.5430	0.0140	0.0710	28.50	16382.10	0.28	2.5783
			7	1030.05	0.6290	0.0150	0.0860	33.25	16499.30	0.28	2.3847

where LST = Level of soil slice thickness, LEL = Levels of compactive effort, e_L = Level of compactive effort Per loading, z = soil slice thickness, Z = total loading, m, E_c = cumulative compactive effort, Nm, ΔZ = compaction, m = mass of soil, γ_{bc} = antecedent bulk density, S_e = degree of saturation, m_c = moisture content, $\Delta Z/Z$ = Cumulative degree of compaction

4 CONCLUSIONS

The multifactor compaction device has shown great potential in compacting 7 cumulative soil slices for the 5 different thicknesses varying from 20 to 100 mm in each case; the device can provide varying compactive efforts from 147.15 Nm to 1030.05 Nm; the compactor covers the whole soil surface under compaction with a single blow, and it is mechanically operated. Results available simulated nominal soil compaction behaviours. This device is easily assembled or disassembled, which makes it suitable to be moved and used where needed. This robust device, which is fabricated, is important because it provides the variables needed for establishing the soil degree of compaction, which is applied in constructing embankments used in constructing stable farm structures on it.

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